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MINIMUM-WEIGHT DESIGN OF SIMPLY SUPPORTED TRANSVERSELY STIFFENED PLATES UNDER COMPRESSION

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SUMMARY

The weight of a simply supported transversely stiffened compression panel subjected to a given buckling load is investigated as a function of the stiffener spacing, plate thickness, and the geometry of the stiffener cross section.

It is shown that there are particular combinations of stiffener spacing and plate thickness, dependent upon the geometrical properties of the stiffener cross section, for which the panel weight is a minimum. Charts are presented to facilitate the determination of these optimum values of stiffener spacing and plate thickness.

INTRODUCTION

The stability under end compression of simply supported flat plates with equally spaced transverse stiffeners (fig. 1) is discussed in reference 1. The stability criterions presented therein are in a form convenient for the determination of the stiffener flexural stiffness required for a plate with transverse stiffeners to support a given compressive load without buckling, provided that the stiffener spacing and the plate length, width, and thickness are known. The total weight of the design so obtained can vary widely, however, depending upon the particular stiffener cross section chosen and the values assumed for the stiffener spacing and plate thickness.

In the present paper the variation in the total weight of a transversely stiffened plate is investigated as a function of the stiffener spacing, plate thickness, and the geometrical properties of the stiffener cross section, with the assumption that only the end compressive load, plate width, and material properties are known. For certain assumed variations of the stiffener area with the stiffener moment of inertia, charts are presented to facilitate the design of the lightest weight panel that can withstand the given load without buckling. The use of these charts is illustrated in the appendix by means of a numerical example.

ASSUMPTIONS

The following basic assumptions are made in the present paper:

(1) The cross sections of the plate are constant and the material is uniform throughout

(2) The stiffeners are identical and equally spaced

(3) The strains are elastic

(4) The plate is infinite in length

(5) The stiffeners have zero torsional stiffness

The principal limitations of the analysis are seemingly imposed by assumptions (4) and (5). An examination of figure 7 in reference 1 indicates that, as regards assumption (4), the analysis presented in the present paper should apply, with reasonable accuracy, to panels with more than four bays and need not be restricted to a plate of infinite length; the assumption that the stiffeners have zero torsional stiffness (assumption (5)) should be sufficiently accurate for most panel designs using open-section stiffeners and is discussed in more detail in the section entitled "Effect of stiffener torsional stiffness."

SYMBOLS

A_r stiffener area

D plate flexural stiffness per unit width $\left(\frac{Et_p^3}{12(1 - \mu^2)}\right)$

E Young's modulus for plate

E_r Young's modulus for stiffener

GJ stiffener torsional stiffness

I_r effective moment of inertia of stiffener attached to plate

$K_n = \frac{A_r}{I_r^{1/n}}$

L stiffener spacing

L_{max} stiffener spacing beyond which no amount of stiffening will maintain stability of the plate for a given compressive load, plate width, and plate thickness $\left(\frac{b}{\frac{\sqrt{k}}{2}\left(1 + \sqrt{1 - \frac{4}{k}}\right)}\right)$

P total critical compressive load on plate

$S = \pi^4\left(\frac{L}{b}\right)^3 \frac{E_r I_r}{bD}$

$T = \pi^2 \frac{L}{b} \frac{GJ}{bD}$

b plate width

k buckling load coefficient $\left(\frac{Pb}{\pi^2 D}\right)$

n integer defining the relationship between A_r and I_r, equal to 2 or 3

t_a average volume of panel material per unit length and width $\left(t_p + \frac{A_r}{L}\right)$

t_p plate thickness

t_s plate thickness required to maintain stability in an infinitely long simply supported unstiffened plate under compression $\left(\sqrt[3]{\frac{3(1 - \mu^2)}{\pi^2} \frac{Pb}{E}}\right)$

$\beta = \frac{L}{b}$

$$\gamma = \frac{E_r I_r}{bD}$$

$$\delta = \frac{t_p}{t_s} = \sqrt[3]{\frac{4}{k}}$$

μ Poisson's ratio for plate

$$\phi = \frac{L}{L_{max}}$$

MINIMUM-WEIGHT ANALYSIS

The total weight of panel material per unit length and width is proportional to an average plate thickness

$$t_a = t_p + \frac{A_r}{L} \tag{1}$$

with

t_p plate thickness

A_r stiffener area

L stiffener spacing

This average plate thickness can vary widely depending upon the particular stiffener area chosen and the values assumed for the stiffener spacing and plate thickness. The analysis is considerably simplified if the variation of stiffener area with effective moment of inertia I_r is known since the moment of inertia, and hence the area, is a function of the plate thickness and stiffener spacing. The problem is then reduced to that of finding the particular values of plate thickness and stiffener spacing that yield the lightest weight panel, provided the buckling load, plate width, material properties, and variation of stiffener area with moment of inertia are known.

Relationships between stiffener area and moment of inertia.- If it is assumed that no panel loads other than the compressive load influence the stiffener design, the optimum stiffener cross section, from the consideration of weight, is the one with the minimum cross-sectional area for any given value of moment of inertia. Hence, the stiffener cross section should be made as deep as possible. If the stiffener cross section is made sufficiently deep, the value of A_r/I_r can be made to approach zero. Practical considerations, of course, prevent this limit from being reached.

Limitations may be imposed on the stiffener cross section other than those on the depth. Two possible limitations are considered.

(1) There may be a maximum allowable value of h/t_r, the length-thickness ratio of any web or flange of the stiffener. Designing for minimum stiffener weight would require that the maximum allowable value of h/t_r be used in all panel designs, unless prevented by other restrictions. If the value of h/t_r is held constant for the stiffeners in different panel designs and if there is geometric similarity of the center lines of the stiffeners, the stiffener area can be shown to vary approximately as the square root of the stiffener moment of inertia.

(2) There may be a minimum allowable value for t_r. If this limitation governs the stiffener design, the minimum stiffener weight is obtained only when the minimum allowable value of t_r is used. If the value of t_r is held constant for the stiffeners of different panel designs and if there is geometric similarity of the center lines of the stiffeners in the different panels, the stiffener area can be shown to vary approximately as the cube root of the stiffener moment of inertia.

The variations of stiffener area with moment of inertia that are considered, therefore, are those that can be expressed as

$$A_r = K_n I_r^{1/n} \qquad (2)$$

where K_n is a constant and n equals 2 or 3. In the case of plates stiffened on one side only, Timoshenko (reference 2) has proposed that the moment of inertia should be computed about the line of contact of stiffener and plate.

The stiffener moment of inertia required to prevent buckling can be expressed by

$$I_r = \frac{bD}{E_r} \gamma \qquad (3)$$

where γ is determined from equation (16) of reference 1 as

$$\gamma = \frac{4\sqrt{k - 4}}{\pi} \frac{\cos B' - \cos A'}{\left(\sqrt{B \sin A'} + \sqrt{A \sin B'}\right)^2} \tag{4}$$

where

$$A = 1 + \sqrt{1 - \frac{4}{k}}$$

$$B = 1 - \sqrt{1 - \frac{4}{k}}$$

$$A' = \frac{\pi\beta\sqrt{k}}{2}\left(1 + \sqrt{1 - \frac{4}{k}}\right)$$

$$B' = \frac{\pi\beta\sqrt{k}}{2}\left(1 - \sqrt{1 - \frac{4}{k}}\right)$$

and

$$\beta = \frac{L}{b}$$

$$k = \frac{Pb}{\pi^2 D}$$

Hence equation (1) can be rewritten as

$$t_a = t_p + \frac{K_n}{L}\left(\frac{bD}{E_r}\gamma\right)^{1/n} \tag{5}$$

Nondimensional parameters.- The plate thickness and stiffener spacing may vary within the limits

$$0 < t_p \leqq t_s$$

$$0 < L \leqq L_{max}$$

where t_s is the plate thickness required to maintain stability in the unstiffened plate $\left(t_s = \sqrt[3]{\frac{3(1-\mu^2)}{\pi^2}\frac{Pb}{E}}\right)$ and L_{max} is the stiffener spacing beyond which no amount of stiffening will maintain stability of the plate for a given compressive load, plate width, and plate thickness $\left(L_{max} = \frac{b}{\frac{\sqrt{k}}{2}\left(1+\sqrt{1-\frac{4}{k}}\right)}\right)$.

In order to represent the results more conveniently, the analysis is made nondimensional by working with the ratios t_p/t_s and L/L_{max} instead of the actual plate thickness and stiffener spacing. Using the symbols

$$\delta = \frac{t_p}{t_s} = \sqrt[3]{\frac{4}{k}}$$

and

$$\phi = \frac{L}{L_{max}}$$

and rearranging equation (5) yields

$$\frac{t_a}{t_s} = \delta + \left[\left(\frac{Pb^2}{E_r}\right)^{1/n}\frac{K_n}{bt_s}\right]\left(\frac{1+\sqrt{1-\delta^3}}{\phi}\right)\left[\frac{2}{\pi^3}\frac{\sqrt{1-\delta^3}}{1-\sqrt{1-\delta^3}}\delta^{\frac{3}{2}(1-n)}\frac{\cos r\pi\phi - \cos \pi\phi}{\left(\sqrt{\frac{1}{r}\sin r\pi\phi}+\sqrt{\sin \pi\phi}\right)^2}\right]^{1/n} \qquad (6)$$

where $r = \frac{1-\sqrt{1-\delta^3}}{1+\sqrt{1-\delta^3}}$.

Minimization.- The plate thickness and stiffener spacing that yield the lightest weight panel are found by minimizing equation (6) with respect to ϕ and δ

$$\frac{\partial\left(\frac{t_a}{t_s}\right)}{\partial\phi} = 0 \tag{7}$$

$$\frac{\partial\left(\frac{t_a}{t_s}\right)}{\partial\delta} = 0 \tag{8}$$

Equation (7) yields

$$\frac{\sin \pi\phi - r \sin r\pi\phi}{\cos \pi\phi - \cos r\pi\phi} + \frac{n}{\pi\phi} + \frac{\frac{\cos \pi\phi}{\sqrt{\sin \pi\phi}} + \frac{\cos r\pi\phi}{\sqrt{\frac{1}{r} \sin r\pi\phi}}}{\sqrt{\sin \pi\phi} + \sqrt{\frac{1}{r} \sin r\pi\phi}} = 0 \tag{9}$$

Values of ϕ or L/L_{max} that give minimum weight for given values of n and δ have been computed from equation (9) and are given in the following table:

k	δ	ϕ	
		n=2	n=3
1000	0.159	0.910	0.950
10	.736	.910	.950
7	.805	.910	.950
5	.928	.911	.950
4.02	.998	.935	.957
4	1.000	1.000	1.000

Where stiffening is required (k greater than 4), this table shows that for values of δ ranging from 0 to 0.9 the panel weight is a minimum, with respect to ϕ, when $\phi = 0.91$ for $n = 2$ and $\phi = 0.95$ for $n = 3$.

Equation (8) yields

$$\left(\frac{Pb^2}{E_r}\right)^{1/n} \frac{K_n}{bt_s} = \frac{2}{3} \frac{\phi}{Z^{1/n}\,\lambda} \tag{10}$$

where

$$Z = \frac{2}{\pi^3} \frac{\sqrt{1 - \delta^3}}{1 - \sqrt{1 - \delta^3}} \delta^{\frac{3}{2}(1-n)} \frac{\cos r\pi\phi - \cos \pi\phi}{\left(\sqrt{\frac{1}{r} \sin r\pi\phi} + \sqrt{\sin \pi\phi}\right)^2}$$

and

$$\lambda = \frac{\delta^2}{\sqrt{1 - \delta^3}} \left\{1 + \frac{1 + \sqrt{1 - \delta^3}}{n} \left[\frac{1}{\sqrt{1 - \delta^3}} + \frac{1}{1 - \sqrt{1 - \delta^3}} + \frac{2\pi\phi}{\left(1 + \sqrt{1 - \delta^3}\right)^2} \frac{\sin r\pi\phi}{\cos r\pi\phi - \cos \pi\phi}\right]\right\}$$

$$+ \frac{1 + \sqrt{1 - \delta^3}}{n} \left[\frac{n - 1}{\delta} + \frac{2}{\sqrt{1 - \delta^3}} \frac{\frac{\delta^2}{\left(1 - \sqrt{1 - \delta^3}\right)^2} \sin r\pi\phi - \frac{\pi\phi}{\delta} \cos r\pi\phi}{\left(\sqrt{\sin \pi\phi} + \sqrt{\frac{1}{r} \sin r\pi\phi}\right)\sqrt{\frac{1}{r} \sin r\pi\phi}}\right]$$

Substituting equation (10) into equation (6) gives

$$\frac{t_a}{t_s} = \delta + \frac{2}{3}\,\frac{1 + \sqrt{1 - \delta^3}}{\lambda} \tag{11}$$

Equations (10) and (11) and the results of equation (9) were used to plot curves for the minimum-weight design of chordwise stiffened plates. Values of t_p/t_s were chosen; and, with L/L_{max} equal to 0.91 for $n = 2$ and 0.95 for $n = 3$, corresponding values of $\left(\frac{Pb^2}{E_r}\right)^{1/n} \frac{K_n}{bt_s}$ and t_a/t_s were computed from equations (10) and (11) and plotted as abscissa and ordinate, respectively. The results for $n = 2$ and $n = 3$ are presented in figures 2 and 3, respectively. With plate width, load, material constants, and the relationship of stiffener area to moment of inertia known, $\left(\frac{Pb^2}{E_r}\right)^{1/n} \frac{K_n}{bt_s}$ is defined; and the curves of figures 2 and 3, with the aid of figure 4, may be used to obtain optimum values of plate thickness and stiffener spacing, as well as the required stiffener area and moment of inertia. The use of these charts is explained by means of an illustrative example in the appendix.

It can be seen from figures 2 and 3 that as the abscissa increases, it becomes more advantageous to use thick-skin construction in which the value of t_p/t_s approaches unity. Indeed, if $\left(\frac{Pb^2}{E_r}\right)^{1/n} \frac{K_n}{bt_s}$ is increased beyond the limiting values 0.361 for $n = 2$ and 0.229 for $n = 3$, the use of stiffeners will yield a panel heavier than the unstiffened plate. Conversely, when the abscissa decreases, it becomes more advantageous to use thin-skin construction in which t_p/t_s approaches zero.

In some cases it may be more convenient to design the panel with L equal to L_{max}, the stiffener spacing at which the plate buckles through the stiffeners. Design curves for L/L_{max} equal to 1.00, plotted in figures 2 and 3, indicate that the increase in weight over the designs for L/L_{max} equal to 0.91 for $n = 2$ and L/L_{max} equal to 0.95 for $n = 3$ is at most 5 percent.

<u>Effect of stiffener torsional stiffness</u>.- One of the assumptions made in this paper is that the effects of stiffener torsional stiffness

on the load-carrying capacity of the stiffened plate are small and may be neglected. The validity of this assumption will now be investigated.

The effect of stiffener torsional stiffness on the buckling load of a chordwise stiffened panel can be determined from figures 2 to 5 of reference 1. From these results the range of plate bay aspect ratio L/b for which the buckling load is only slightly increased (increased by less than 5 percent) by the stiffener torsional stiffness can be determined. The design criterions presented in this paper, based on the assumption of zero torsional stiffness, can reasonably be assumed to apply for this range of L/b. Because the design criterions in this paper indicate that the most efficient panel design is obtained when L/L_{max} is approximately equal to 1, the effect of stiffener torsional stiffness on the buckling load is investigated only in the region immediately adjacent to the cut-off lines in figures 2 to 5.

Let the stiffener flexural-stiffness parameter $\pi^4\left(\frac{L}{b}\right)^3\frac{E_rI_r}{bD}$ be denoted by S and the stiffener torsional stiffness parameter $\pi^2\frac{L}{b}\frac{GJ}{bD}$ be denoted by T. Then

$$\frac{S}{T} = \frac{\pi^4\left(\frac{L}{b}\right)^3\frac{E_rI_r}{bD}}{\pi^2\frac{L}{b}\frac{GJ}{bD}}$$

$$= \pi^2\left(\frac{L}{b}\right)^2\frac{E_rI_r}{GJ}$$

from which

$$\frac{1}{\pi}\sqrt{\frac{GJ}{E_rI_r}} = \frac{L/b}{\sqrt{S/T}} \tag{12}$$

If corresponding values of L/b and $\sqrt{S/T}$ for which the buckling load is increased 5 percent over that for $T = 0$ are known, corresponding values of the parameter $\frac{1}{\pi}\sqrt{\frac{GJ}{E_rI_r}}$ that cause this increase may be obtained from equation (12). These values of L/b and $\sqrt{S/T}$ were obtained from figures 2 to 5 of reference 1 and were used to construct the curve of figure 5 herein.

If, for a given stiffener, the actual value of L/b for the panel is greater than the value given by the curve of figure 5, the error in load carrying capacity is less than 5 percent and may be neglected. If the value of L/b is less than the value given by the curve, the error is more than 5 percent and the effects of stiffener torsional stiffness should be investigated more thoroughly.

The following example illustrates the use of figure 5 for a Z-section stiffener. The web depth h_w is assumed equal to twice the flange width, and the stiffener thickness t_r is assumed uniform throughout. If G, the shear modulus of elasticity, is equal to $E_r/2.66$,

$$\frac{1}{\pi}\sqrt{\frac{GJ}{E_r I_r}} = \frac{0.177}{h_w/t_r}$$

For a value of h_w/t_r of 15,

$$\frac{1}{\pi}\sqrt{\frac{GJ}{E_r I_r}} = 0.0118$$

and, from figure 5, the effect of stiffener torsional stiffness may be neglected if L/b is greater than 0.14.

If the upper flange is removed from the assumed Z-section, the resulting stiffener is an angle for which

$$\frac{1}{\pi}\sqrt{\frac{GJ}{E_r I_r}} = \frac{0.228}{h_w/t_r}$$

If h_w/t_r is again equal to 15,

$$\frac{1}{\pi}\sqrt{\frac{GJ}{E_r I_r}} = 0.0152$$

and, from figure 5, the effect of stiffener torsional stiffness may be neglected if L/b is greater than 0.18.

Lower limits on the values of L/b for which the effect of stiffener torsional stiffness may be neglected may be obtained in a similar manner for stiffeners with other cross-sectional shapes and dimensions.

CONCLUDING REMARKS

The weight of a simply supported transversely stiffened compression panel subjected to a given buckling load has been investigated as a function of the stiffener spacing, plate thickness, and the geometry of the stiffener cross section.

It has been shown that there are particular combinations of stiffener spacing and plate thickness, dependent upon the geometrical properties of the stiffener cross section, for which the panel weight is a minimum. Charts have been presented to facilitate the determination of these optimum values of stiffener spacing and plate thickness.

The effect of stiffener torsional stiffness upon the design criterions has been investigated. A chart has been presented giving the range of plate bay aspect ratio for which the torsional stiffness of a given stiffener increases the buckling load by 5 percent or less. It can be reasonably assumed that the design criterions of this paper, based upon the assumption of zero torsional stiffness, will apply for this range of plate bay aspect ratio.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., August 2, 1948

APPENDIX

NUMERICAL EXAMPLE

As an illustration of the application of figures 2 and 3 to a design problem, a plate with transverse Z-section stiffeners (see fig. 1) will be designed in accordance with the two criterions developed in this paper.

Plate design illustrating use of figure 2.- The plate width b is 25 in. and the load P to be carried is 10,000 lb; μ and E for the plate and stiffener material are 0.33 and 10.5×10^6 psi, respectively. The web depth of the stiffeners is twice the flange width, and the ratio of web depth to stiffener thickness is 25.

Under these conditions the area of the stiffener varies directly as the square root of the moment of inertia, with the constant of proportionality K_2 equal to 0.438. Figure 2 must then be used, with

$$\frac{L}{L_{max}} = 0.91$$

and

$$\left(\frac{Pb^2}{E_r}\right)^{1/2} \frac{K_2}{bt_s} = \frac{\frac{0.438}{25}\left(\frac{10000 \times 25^2}{10.5 \times 10^6}\right)^{1/2}}{\left[\frac{3}{\pi^2}\left(1 - 0.33^2\right)\frac{10000 \times 25}{10.5 \times 10^6}\right]^{1/3}}$$

$$= 0.0730$$

With these values of $\left(\frac{Pb^2}{E_r}\right)^{1/2} \frac{K_2}{bt_s}$ and L/L_{max}, the optimum values of t_p/t_s and t_a/t_s are, from figure 2,

$$\frac{t_p}{t_s} = 0.46$$

$$\frac{t_a}{t_s} = 0.65$$

Since

$$t_s = \sqrt[3]{\frac{3}{\pi^2}\left(1 - 0.33^2\right)\frac{10000 \times 25}{10.5 \times 10^6}}$$

$$= 0.185 \text{ in.}$$

the plate thickness for minimum weight is

$$t_p = 0.46 \times 0.185$$

$$= 0.085 \text{ in.}$$

and the average plate thickness is

$$t_a = 0.65 \times 0.185$$

$$= 0.120 \text{ in.}$$

from which

$$\frac{A_r}{L} = 0.120 - 0.085$$

$$= 0.035 \text{ in.}$$

With t_p/t_s known, the stiffener spacing may be determined as follows:

From figure 4, with $\dfrac{t_p}{t_s} = 0.46$,

$$\frac{L_{max}}{b} = 0.16$$

and

$$L = 0.91 \times 25 \times 0.16$$

$$= 3.64 \text{ in.}$$

Therefore

$$A_r = 0.035 \times 3.64$$

$$= 0.127 \text{ in.}^2$$

and from the relation between A_r and I_r given by equation (2)

$$I_r = \left(\frac{0.127}{0.438}\right)^2 = 0.084 \text{ in.}^4$$

The required stiffener dimensions are

Web depth = 1.25 in.

Flange width = 0.63 in.

Thickness = 0.05 in.

<u>Plate design illustrating use of figure 3</u>.- The panel designed in the previous design problem will be redesigned with stiffeners having a thickness of 0.050 and a ratio of web depth to flange width of 2. Under these conditions the area of the stiffener varies approximately as the cube root of the moment of inertia, with the constant of proportionality K_3 equal to 0.390. Figure 3 must then be used, with

$$\frac{L}{L_{max}} = 0.95$$

and

$$\left(\frac{Pb^2}{E_r}\right)^{1/3} \frac{K_3}{bt_s} = \frac{0.390}{25 \times 0.185}\left(\frac{10000 \times 25^2}{10.5 \times 10^6}\right)^{1/3}$$

$$= 0.0710$$

With these values of $\left(\frac{Pb^2}{E_r}\right)^{1/3} \frac{K_3}{bt_s}$ and L/L_{max}, the optimum values of t_p/t_s and t_a/t_s are, from figure 3,

$$\frac{t_p}{t_s} = 0.49$$

$$\frac{t_a}{t_s} = 0.72$$

Then, since $t_s = 0.185$ in., the plate thickness for minimum weight is

$$t_p = 0.49 \times 0.185$$

$$= 0.091 \text{ in.}$$

and the average plate thickness is

$$t_a = 0.72 \times 0.185$$

$$= 0.133 \text{ in.}$$

from which

$$\frac{A_r}{L} = 0.133 - 0.091$$

$$= 0.042 \text{ in.}$$

With t_p/t_s known, the stiffener spacing may be determined as follows:

From figure 4, with $\frac{t_p}{t_s} = 0.49$,

$$\frac{L_{max}}{b} = 0.18$$

and

$$L = 0.95 \times 0.18 \times 25$$

$$= 4.28 \text{ in.}$$

Therefore

$$A_r = 0.42 \times 4.28$$

$$= 0.180 \text{ in.}^2$$

and

$$I_r = \left(\frac{0.180}{0.390}\right)^3 = 0.099 \text{ in.}^4$$

The required stiffener dimensions are

Web depth = 1.80 in.

Flange width = 0.90 in.

Thickness = 0.05 in.

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2. Timoshenko, S.: Theory of Elastic Stability. McGraw-Hill Book Co., Inc., 1936, p. 377.

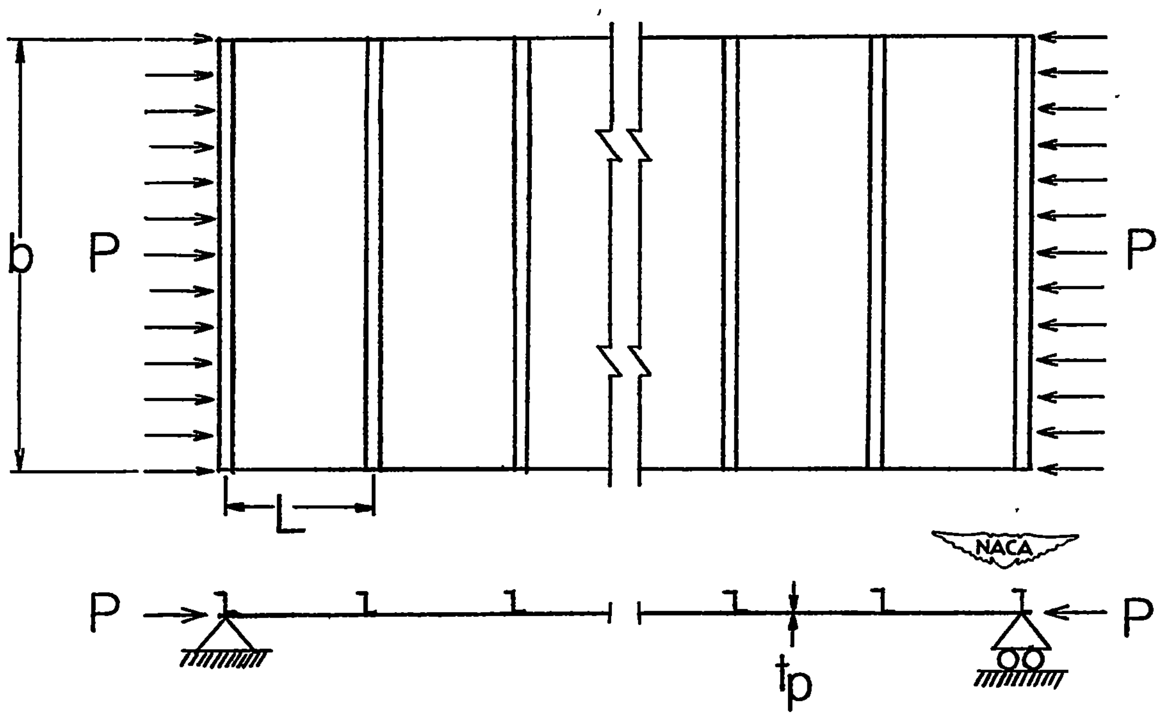

Figure 1.- Simply supported plate with transverse stiffeners.

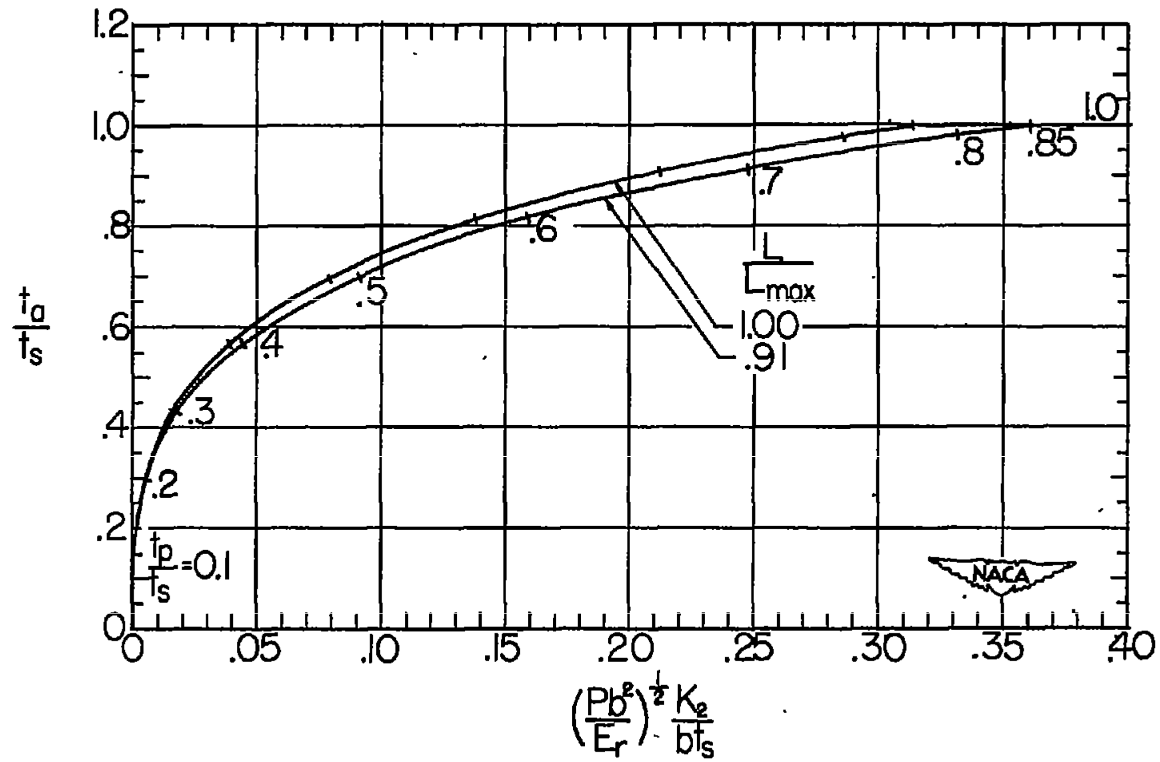

Figure 2.- Minimum-weight-design curves for simply supported plates with transverse stiffeners (n = 2).

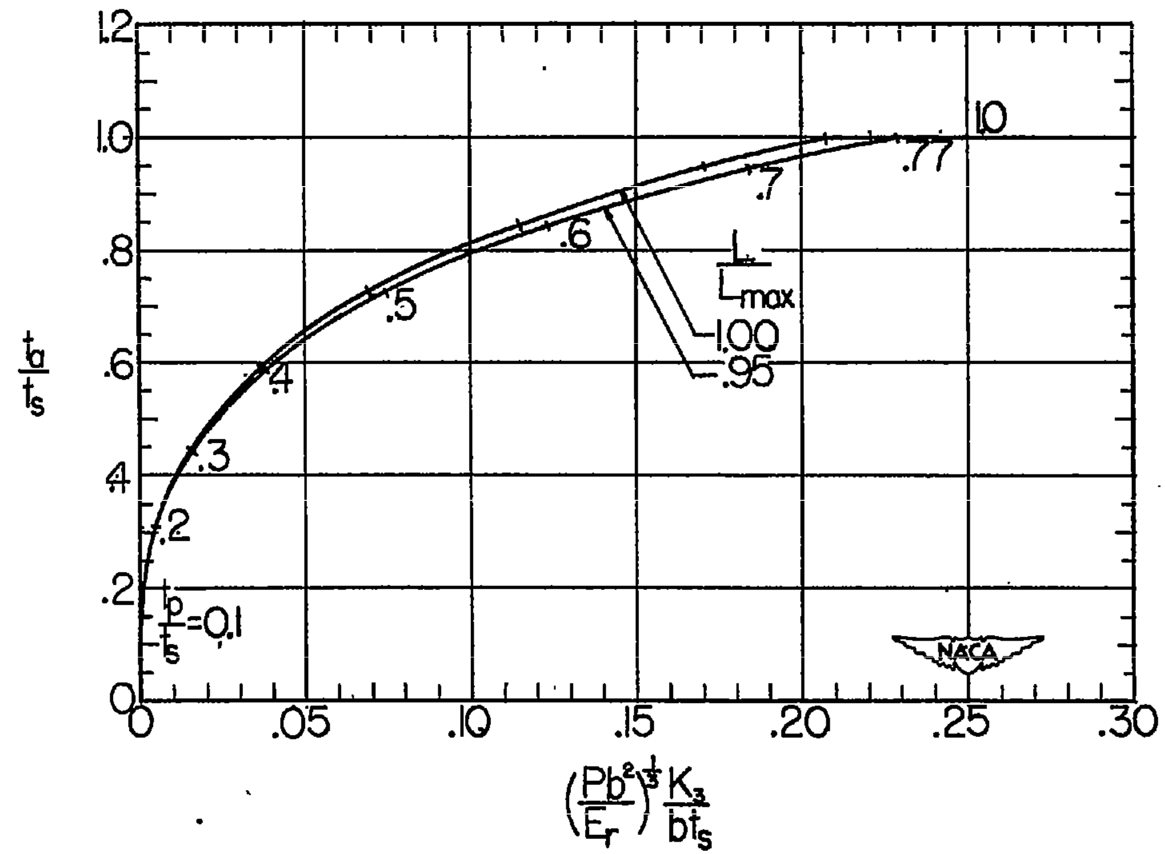

Figure 3.- Minimum-weight-design curves for simply supported plates with transverse stiffeners (n = 3).

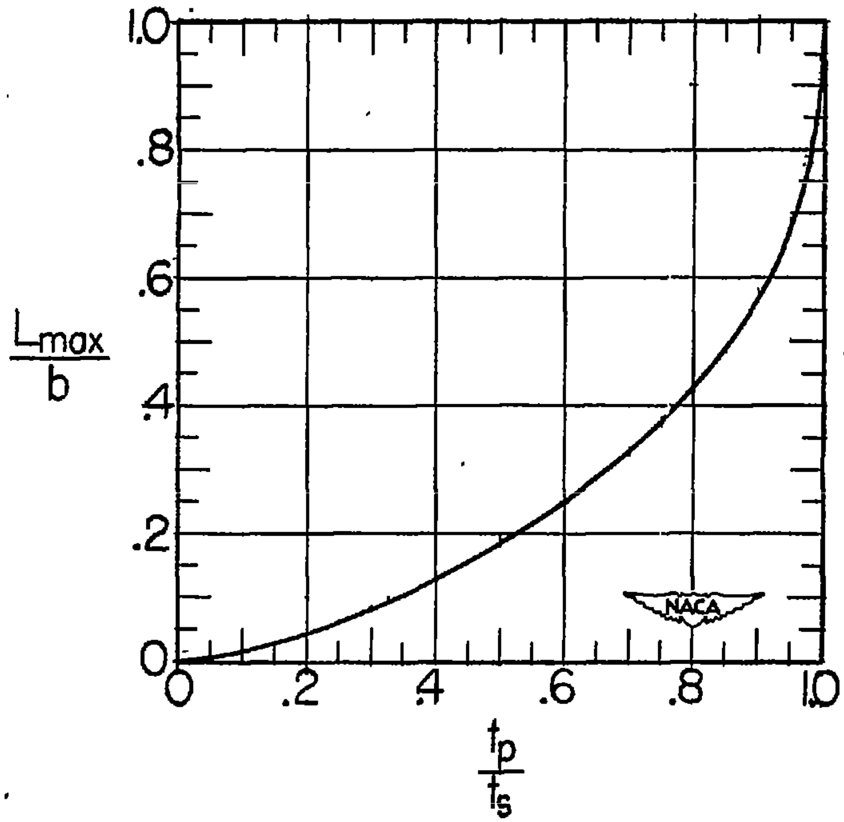

Figure 4.- Stiffener spacing beyond which plate stability cannot be maintained.

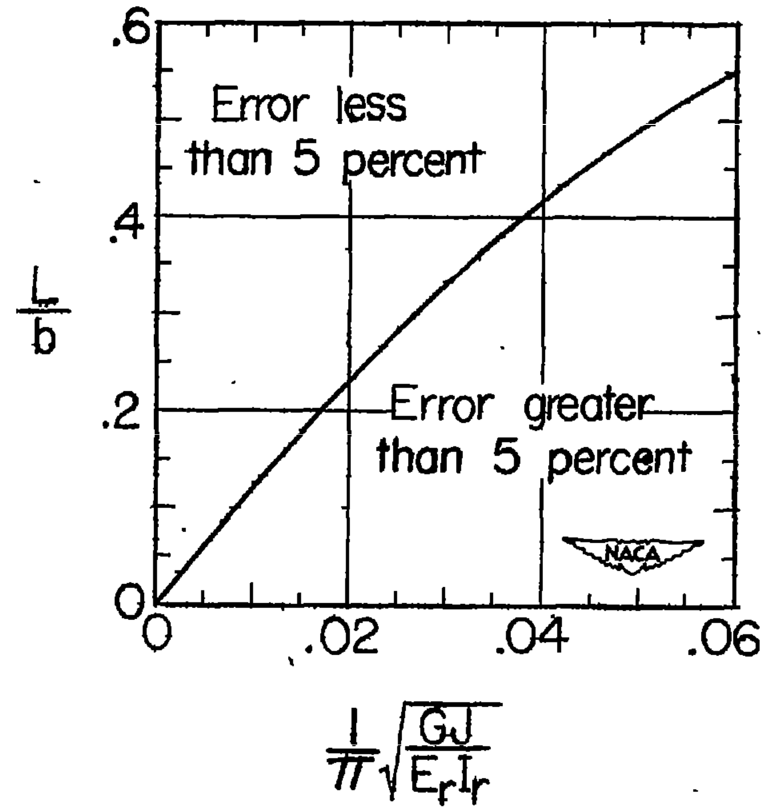

Figure 5.- Error in panel load-carrying capacity caused by neglect of stiffener torsional stiffness.